

Modelling of hybrid energy system—Part I: Problem formulation and model development

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ABSTRACT

A well designed hybrid energy system can be cost effective, has a high reliability and can improve the quality of life in remote rural areas. The economic constraints can be met, if these systems are fundamentally well designed, use appropriate technology and make use effective dispatch control techniques. The first paper of this tri-series paper, presents the analysis and design of a mixed integer linear mathematical programming model (time series) to determine the optimal operation and cost optimization for a hybrid energy generation system consisting of a photovoltaic array, biomass (fuelwood), biogas, small/micro-hydro, a battery bank and a fossil fuel generator. The optimization is aimed at minimizing the cost function based on demand and potential constraints. Further, mathematical models of all other components of hybrid energy system are also developed. This is the generation mix of the remote rural of India; it may be applied to other rural areas also.

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1. Introduction

Hybrid Energy Systems (HES) generally integrate renewable energy sources with fossil fuel powered diesel/petrol generator to provide electric power where the electricity is either fed directly into the grid or to batteries for energy storage. The role of integrating renewable energy in a hybrid energy system is primarily to save diesel fuel.

A hybrid energy system may or may not be connected to the grid. They are generally independent of large centralized electric grids and are used in rural remote areas. In these systems it is possible for the individual power sources to provide different percentages of the total load.

For systems employing totally clean renewable energy, high capital cost is an important barrier. However, we can produce green power by adding different renewable energy sources to diesel generator and battery, which is also called a hybrid energy system. This kind of system can compromise investment cost, diesel fuel usage cost and also operation and maintenance costs.

There are generally two accepted hybrid energy system configurations:

- Systems based mainly on diesel generators with renewable energy used for reducing fuel consumption.
- Systems relying on the renewable energy source with a diesel generator used as a back-up supply for extended periods of low renewable energy input or high load demand.

2. Literature review

Mathematical optimization techniques which have previously been used to optimize hybrid energy system (or remote area power system) operation include linear programming [1], quadratic programming [2], mixed integer non-linear programming [3], mixed integer linear programming [4], generalized network flow programming [5], discrete dynamic programming [6], stochastic discrete dynamic programming [7], analytical model [8], probabilistic method [9], iterative method [10], and other methods [11–15].

Literature review also reveals that the modelling of hybrid energy system and their application in decentralized mode are quite limited. The models developed so far mainly focus on rural areas and not individual villages, cluster of villages, blocks, or district. Very limited efforts are reported for block level planning and are not based on any optimization approach. Further, attempts for developing optimum energy mix of different resources for meeting the energy needs of the rural people are also limited [16,17].

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3. Problem formulation

From the literature, it is observed that lot of work has been carried out for modelling of hybrid energy system. The renewable energy resources considered under these studies are mainly solar photovoltaic, biomass, and wind but a very little work has been reported for the modelling of hybrid energy system involving small hydro/micro-hydro power in combination with conventional system.

The main objective of the study is to develop a model of hybrid energy system with more emphasis on small hydro/micro-hydro power with biogas power, biomass (fuelwood) power, solar photovoltaic power as a renewable power, and battery bank, diesel power as a conventional power for a remote rural area in cost effective manner. The aim of this model is to identify the most economic and appropriate power supply for electrification of a selected remote rural area consisting cluster of villages.

Hence, in this paper, a mixed integer linear programming model, which is a special type of mathematical programming model, is developed to solve the problem of designing hybrid energy systems.

4. Hybrid energy system configuration

The block diagram for a typical stand-alone hybrid energy system, based on a generalized three-bus configuration is shown in Fig. 1. The system consists of micro-hydro generator (MHG), biogas generator (BGG), biomass (fuelwood) generator (BMG), photovoltaic generator (PVG), battery bank storage, back-up diesel generator (DEG), and dump load.

Provisions for the availability of both AC and DC buses are made using electronic converters. To serve the load, electrical energy can be produced either directly from renewable generators and diesel generator, or indirectly from the battery bank. These relationships are expressed in Eqs. (1.1) through (1.5).

$$E_{PVG}(t) = E_{PVG, Load}(t) + E_{PVG, BATT}(t) + E_{PVG, Dump}(t) \quad (1.1)$$

$$E_{MHG}(t) = E_{MHG, Load}(t) + E_{MHG, BATT}(t) + E_{MHG, Dump}(t) \quad (1.2)$$

$$E_{BGG}(t) = E_{BGG, Load}(t) + E_{BGG, BATT}(t) + E_{BGG, Dump}(t) \quad (1.3)$$

$$E_{BMG}(t) = E_{BMG, Load}(t) + E_{BMG, BATT}(t) + E_{BMG, Dump}(t) \quad (1.4)$$

$$E_{DEG}(t) = E_{DEG, Load}(t) + E_{DEG, BATT}(t) + E_{DEG, Dump}(t) \quad (1.5)$$

In any hour t , the energy available to charge the battery bank (BATT) is shown in Eq. (1.6), and the energy available from the battery to serve the load are shown in Eq. (1.7).

$$E_{BATT, IN}(t) = \eta_{CHG} \times \eta_{CC} \times [E_{PVG, BATT}(t) + \eta_{REC} \times (E_{MHG, BATT}(t) + E_{BGG, BATT}(t) + E_{BMG, BATT}(t) + E_{DEG, BATT}(t))] \quad (1.6)$$

$$E_{BATT, Load}(t) = \eta_{DCHG} \times [E_{BATT, IN}(t)] \quad (1.7)$$

Finally, the total energy available to serve the load is written in Eq. (1.8).

$$E_{Load}(t) = [E_{MHG, Load}(t) + E_{BGG, Load}(t) + E_{BMG, Load}(t) + E_{DEG, Load}(t) + \eta_{INV} \times (E_{PVG, Load}(t) + E_{BATT, Load}(t))] \quad (1.8)$$

where $E_j(t)$ is the energy output from technology j , $E_{j, Load}(t)$ energy output from technology j directed to load, $E_{j, BATT}(t)$ energy output from technology j directed to battery, $E_{j, Dump}(t)$ excess energy output from technology j directed to dump load, $E_{BATT, IN}(t)$ energy input to battery, and j stands for MHG, BGG, BMG, PVG, DEG, and BATT.

5. System component modelling

Hybrid energy system components model with general description is described below:

5.1. Mathematical model of micro-hydro generator

The hydro power usually refers to the generation of shaft power from falling water. The power is then used for direct

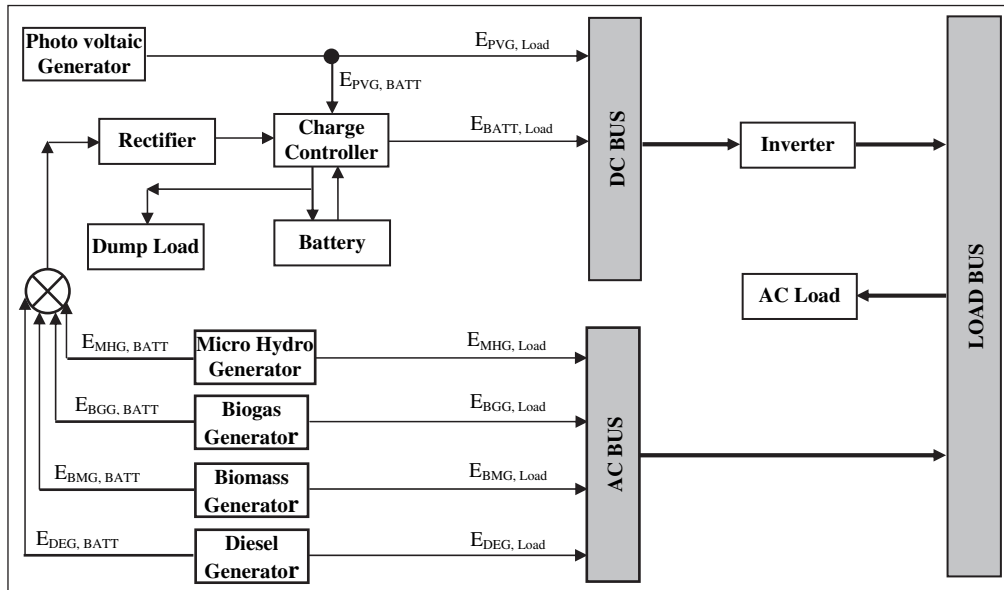


Fig. 1. The configuration of hybrid energy system.

mechanical purposes or, more frequently, for generating electricity. The theoretical electrical power generated by the micro-hydro unit is given by

$$P_{MHG}(t) = 9.81 \times Q \times \rho \times h \quad (2.1)$$

and the total energy in kWh in an hour t is given by

$$E_{MHG}(t) = P_{MHG}(t) \times \eta_{MHG} \quad (2.2)$$

where P_{MHG} is the rated power, $E_{MHG}(t)$ hourly energy output, Q discharge in m^3/s , ρ density of water, h head in m, and η_{MHG} is the overall efficiency of micro-hydro unit.

5.2. Mathematical model of biomass generator

As an energy resource, biomass is very versatile in terms of the variety of forms. To simplify our study, we will concentrate only on fuelwood in this section.

A biomass gasifier based electricity generation system consists of biomass preparation unit, biomass gasifier, gas cooling and cleaning system, internal combustion engine suitable for operation in dual fuel mode, and electric generator. The producer gas obtained from fuelwood can be used to generate power using a diesel engine with diesel as pilot fuel and producer gas as main fuel [18].

The annual delivered electricity output (E_{Annual}) of a biomass gasifier energy system with rated power output of electricity generator is dependent on its capacity utilization factor (CUF). Assuming 21% conversion efficiency from fuelwood to electricity, it can be modelled using the following expression [18]:

$$E_{Annual} = P_{BMG}(8760 \times CUF) \quad (3.1)$$

and hourly energy output is given by

$$E_{BMG}(t) = P_{BMG}(t) \times \eta_{DFEG} \quad (3.2)$$

where P_{BMG} is the rated power of biomass generator, $E_{BMG}(t)$ hourly energy output of biomass generator, and η_{DFEG} is the efficiency of dual fuel engine generator.

5.3. Mathematical model of biogas generator

Biogas can be produced from livestock manure and human sewage. A biogas based electricity generation system consists of a digester, a biogas collection tank, internal combustion engine, a generator as well as the piping and controls required for successful operation. The biogas is produced in the anaerobic digester. This biogas can be used to generate power using a diesel engine with diesel as a pilot fuel and biogas as main fuel [19].

Assuming 27% conversion efficiency from biogas to electricity, it can be modelled using the following expression as explained above:

$$E_{Annual} = P_{BGG}(8760 \times CUF) \quad (4.1)$$

and hourly energy output is given by

$$E_{BGG}(t) = P_{BGG}(t) \times \eta_{DFEG} \quad (4.2)$$

where P_{BGG} is the rated power, and $E_{BGG}(t)$ is the hourly energy output of biogas generator.

5.4. Mathematical model of SPV generator

Solar photovoltaic (SPV) technology involves the direct conversion of sunlight into electricity through the use of photovoltaic array. The sunlight impinging on panels, i.e. irradiance

(incoming solar radiation), is measured in units W/m^2 . The PV system power output (DC) has approximately a linear relationship to the insolation. Using the solar radiation available on the tilted surface the hourly energy output of the PV generator, can be calculated according to the following equation [20]

$$E_{PVG}(t) = G(t) \times A \times \eta_{PVG} \quad (5.1)$$

where $G(t)$ is the hourly irradiance in kWh/m^2 , A surface area of the PV modules in m^2 , $E_{PVG}(t)$ hourly energy output from PV, and η_{PVG} is the efficiency of PV generator.

All the energy losses in a PV generator, including connection losses, wiring losses and other losses, are assumed to be zero. Eq. (5.1) assumes that PV generator has a tracking system and a maximum power point tracker (i.e. $\eta = 1$). It also assumes that the temperature effects (on PV cells) are ignored.

5.5. Mathematical model of diesel generator

Conventional generators are normally diesel engines coupled to generator. Diesel generators supply energy in one of two ways. Either they generate only the power needed by the load (load following), or they generate at nominal power and the surplus energy (if any), is used to charge the battery bank. In this study, a diesel generator of both kinds is considered. The generator model is designed in such a way that the diesel generator is always operate between 80–100% of their kW rating, while operating in conjunction with the battery bank and other renewable generators [21]. Energy generated by diesel generator in an hour t is defined by the following expression:

$$E_{DEG}(t) = P_{DEG}(t) \times \eta_{DEG} \quad (6.1)$$

where P_{DEG} is the rated power, $E_{DEG}(t)$ is the hourly energy output, and η_{DEG} is the efficiency of diesel generator.

5.6. Mathematical model of rectifier

The rectifier is used to transform the surplus AC power from the MHG, BGG, BMG, DEG to DC power of constant voltage (when the energy generated by the hybrid energy system exceeds the load demand). The rectifier model is given below:

$$E_{REC-OUT}(t) = E_{REC-IN}(t) \times \eta_{REC} \quad (7.1)$$

$$E_{REC-IN}(t) = E_{SUR-AC}(t) \quad (7.2)$$

at any time t ,

$$E_{SUR-AC}(t) = E_{MHG}(t) + E_{BGG}(t) + E_{BMG}(t) + E_{DEG}(t) - E_{Load}(t) \quad (7.3)$$

where $E_{REC-OUT}(t)$, $E_{REC-IN}(t)$ is hourly energy output and input from rectifier respectively, $E_{SUR-AC}(t)$ amount of surplus energy from AC sources, and η_{REC} is the efficiency of rectifier.

5.7. Mathematical model of charge controller

To prevent overcharging of a battery, a charge controller is used to sense when the batteries are fully charged and to stop or decrease the amount of energy flowing from the energy source to the batteries. The model of the charge controller is presented below:

$$E_{CC-OUT}(t) = E_{CC-IN}(t) \times \eta_{CC} \quad (8.1)$$

$$E_{CC-IN}(t) = E_{REC-OUT}(t) + E_{SUR-DC}(t) \quad (8.2)$$

where $E_{\text{SUR-DC}}(t)$ is the amount of surplus energy from DC sources, $E_{\text{CC-OUT}}(t)$, $E_{\text{CC-IN}}(t)$ is hourly energy output and input from charge controller respectively, and η_{CC} is charge controller efficiency.

5.8. Mathematical model of inverter

The photovoltaic generator and battery produce DC power and therefore when the hybrid energy system contains an AC load, a DC/AC conversion is required. The inverter model for photovoltaic generator and battery bank are given below:

$$E_{\text{PVG-INV}}(t) = E_{\text{PVG}}(t) \times \eta_{\text{INV}} \quad (9.1)$$

$$E_{\text{BATT-INV}}(t) = [(E_{\text{BATT}}(t-1) - E_{\text{Load}}(t))/(\eta_{\text{INV}} \times \eta_{\text{DCHG}})] \quad (9.2)$$

where $E_{\text{PVG-INV}}(t)$ is the hourly energy output from inverter (in case of SPV), $E_{\text{BATT-INV}}(t)$ hourly energy output from inverter (in case of battery), and η_{INV} is the efficiency of inverter.

5.9. Mathematical model of battery bank

At any hour t the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from $t-1$ to t . During the charging process, when the total output of all generators is greater than the load demand, the available battery bank capacity at hour t can be described by

$$E_{\text{BATT}}(t) = E_{\text{BATT}}(t-1) + E_{\text{CC-OUT}}(t) \times \eta_{\text{CHG}} \quad (10.1)$$

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at hour t can be expressed as:

$$E_{\text{BATT}}(t) = E_{\text{BATT}}(t-1) - E_{\text{Needed}}(t) \quad (10.2)$$

$$E_{\text{Needed}}(t) = E_{\text{Netload}}(t)/(\eta_{\text{INV}} \times \eta_{\text{DCHG}}) \quad (10.3)$$

where $E_{\text{Needed}}(t)$ is the hourly energy needed by the load side, $E_{\text{Netload}}(t)$ hourly energy of load demand, $E_{\text{BATT}}(t)$, $E_{\text{BATT}}(t-1)$ is energy stored in battery at hour t and $t-1$ respectively, and η_{CHG} , η_{DCHG} is the battery charging and discharging efficiency respectively.

Meanwhile, the charged quantity of the battery is subject to the following constraints:

$$\text{SOC}_{\min} \leq \text{SOC}(t) \leq \text{SOC}_{\max} \quad (10.4)$$

The maximum value of SOC is 1, and the minimum SOC is determined by maximum depth of discharge (DOD),

$$\text{SOC}_{\min} = 1 - \text{DOD} \quad (10.5)$$

5.10. Mathematical model of dump load

The dump energy is defined as the energy produced by the renewable generators or diesel generator but unused when the load does not need all the energy and the battery has reached its maximum capacity and can not store more energy [20]. In this study, a conventional electric water heater is assumed as dump load. The hourly dump energy is calculated as follows:

$$E_{\text{Dump}}(t) = E_{\text{CC-OUT}}(t) - [(E_{\text{BATMAX}} - E_{\text{BATT}}(t-1))/\eta_{\text{CHG}}] \quad (11.1)$$

Negative results are assumed as zero dump energy.

where $E_{\text{DUMP}}(t)$ is total dump energy at time t , and E_{BATMAX} is maximum capacity of battery.

5.11. Mathematical model of load demand

The load demand determines the total energy demand, E_{Load} , requested by the load model of the system for each time step in the simulation. In this case, there are four types of electrical loads: Household load (Lighting load, T.V., Fan, and Radio), Commercial load (small shops lighting and floor mill), Industrial load (saw mill/paddy huller), and Community load (Primary health centre lighting, street lighting, school lighting). Thus, the energy demand of the loads can be expressed as:

$$E_{\text{Load}}(t) = E_{\text{HHL}}(t) + E_{\text{COL}}(t) + E_{\text{INL}}(t) + E_{\text{CNL}}(t) \quad (12.1)$$

$$E_{\text{HHL}}(t) = E_{\text{COL}}(t) = E_{\text{INL}}(t) = E_{\text{CNL}}(t) = \sum_{i=1}^N [P_i \times t_i \times n] \quad (12.2)$$

where $E_{\text{Load}}(t)$ is the total hourly load at time t , $E_{\text{HHL}}(t)$ hourly household load at time t , $E_{\text{COL}}(t)$ hourly commercial load at time t , $E_{\text{INL}}(t)$ hourly industrial load at time t , $E_{\text{CNL}}(t)$ hourly community load at time t , P_i power consumed by appliance i , t_i time of appliance usage, n number of devices, i type of device, and N is the number of electric appliance used.

6. Development of model

This section describes an optimization technique developed for the design of a hybrid energy system. The design takes into account the unit cost of different resources based on life cycle costs. The problem is formulated as a mixed integer linear programming [4,22,23].

The mathematical approach is presented in a simple and useful form directly applicable for the modelling of stand-alone hybrid energy system for use in the remote rural areas. The input data required, assumptions involved, and the design procedure are clearly explained. The approach involves the minimization of a cost function subject to a set of equality and inequality constraints.

6.1. Model assumptions

In order to state a model which is both sufficiently general and accurate for describing all types of energy flow, we make following assumptions and simplifications:

- We consider the system in steady state.
- We consider the steady state power, efficiency, and energy only, no other values are used for the system description.
- The model incorporates conservation laws (e.g. conservation of flow) but no constitutional laws (e.g. relation between voltage and current).
- Since the electrification process is continuous, it is assumed that the hybrid generation system operates on a 24 h a day and therefore equipment breakdowns, planned maintenance etc., are not explicitly considered.
- It is assumed that the costs are additive and that there are no perceptual changes in other factors such as plant capacity, unit cost of different energy sources, configuration of energy system etc.
- It is assumed that only AC appliances are used and are connected to the load bus.
- A time horizon of 1 h is used throughout this study.

- It is further assumed that the village electrical load and the renewable sources are constant within each one-hour time step.

The unit of measurement for power is kW and that for electrical energy is kWh. It is assumed that all the system components shown in Fig. 1 are installed at a specific site.

6.2. Objective function

The main objective function to determine the optimum cost of a hybrid energy system is expressed as:

$$\text{Minimize : TC} = \sum_{d=1}^{dn} \sum_{j=1}^6 \sum_{t=1}^{24} [C_j \times E_{jdt}] \quad (13.1)$$

where TC is the total optimized cost of providing energy for all end uses for operation of the system, C_j cost/unit of the j th generating unit (Rs/kWh), E_{jdt} optimal amount of the energy of the generating unit j for end use in a day d , hour t for a particular month, dn is number of days depending upon a particular month, and j is a type of energy source.

In addition to that, the diesel engine generator is desired to be operated under constant output with high efficiency in order to reduce the polluting gases from the diesel engine; therefore, other secondary objectives of the model are as follows

1. Keep the output of the diesel generator constant with high efficiency.
2. Minimize the fuel consumption of the diesel generator.
3. Minimize the frequency of diesel generator starts/stops.
4. Maximize the utilization rate of the renewable energy sources.

6.3. Integer variable constraints

Integer variables are used for representing the operation or otherwise of the different renewable generators, diesel generator, and battery bank. Let X_{MHG} , X_{BGG} , X_{BMG} , X_{PVG} , X_{DEG} , and X_{BATT} be the 0–1 integer variables representing the decisions to select or not select MHG, BGG, BMG, PVG, DEG, and BATT components respectively, of the hybrid energy system. That is,

$$X_j = \begin{cases} 1 & \text{If unit } j \text{ serves the load directly} \\ 0 & \text{Otherwise} \end{cases} \quad (13.2)$$

6.4. General constraints

The optimization is to be performed, enforcing a set of restrictions, which can be classified in the following groups:

1. **Energy balance constraint:** The hourly energy generation sum of all on-line units must equal the system load demand over the whole scheduling time range. That is

$$E_{j, j \neq BATT}(t) \pm E_{BATT}(t) \geq E_{Load}(t) + E_{Dump}(t) \quad (13.3)$$

where $+E_{BATT}(t)$, $-E_{BATT}(t)$ is the energy supplied and used by the battery respectively.

2. **Individual capacity constraint:** The power supplied by each generator must be less than or equal to the capacity of the unit.

$$P_j(t) \leq Cap_j \quad \text{for all } t \quad (13.4)$$

3. **Unit generation limits:** Each generation unit has its maximum and minimum generation limit. Therefore, in order to avoid damages, the hourly generation of each unit must meet constraints as follows:

$$P_{jmin} \leq P_j(t) \leq P_{jmax} \quad \text{for all } t \quad (13.5)$$

4. **Battery storage limits:** The energy stored in batteries at any hour t is subject to the following constraints:

$$E_{BATTmin} \leq E_{BATT}(t) \leq E_{BATTmax} \quad \text{for all } t \quad (13.6)$$

$$E_{BATTmin} = (1 - DOD)E_{BATTmax} \quad (13.7)$$

where $E_{BATTmin}$, $E_{BATTmax}$ are the minimum and maximum energy stored in battery.

This means that the batteries should not be over discharged or over charged at any time. That protects batteries from being damaged.

5. **Non-negativity constraints:** Since electrical energy flow and power flow cannot be negative in the solution. Hence, all the decision variables are non-negative.

6.5. Decision variables and constraints associated with PVG

Decision variables of photovoltaic generator are $X_{j=PVG}$, and $E_{jdt, j=PVG}$. The former is an integer decision variable representing a decision to select or not select a photovoltaic generator (PVG) in an hour t ; where as the latter is a continuous decision variable representing power generation from photovoltaic generator in day d , and hour t of a particular month. The following equations represent the generation characteristics of PVG. They imply that the power generation from the PVG at any hour t can take the value at its maximum generation capacity, if the PVG is selected.

$$E_{jdt}(t) = E_{jdt, Load}(t) < [G(t) \times A \times \eta_{PVG}] \times X_{j=PVG} \quad (13.8)$$

i.e.

$$\begin{aligned} E_{jdt}(t) &= E_{jdt, Load}(t) + E_{jdt, BATT}(t) + E_{jdt, Dump}(t) \\ &= G(t) \times A \times \eta_{PVG} \end{aligned}$$

$$E_{jdt}(t) = E_{jdt, Load}(t) \geq [G(t) \times A \times \eta_{PVG}] \times X_{j=PVG} \quad (13.9)$$

i.e.

$$E_{jdt}(t) = E_{jdt, Load}(t) = G(t) \times A \times \eta_{PVG}$$

6.6. Decision variables and constraints associated with MHG

Similarly, the following equations represent the generation characteristics and constraints associated with MHG

$$E_{jdt}(t) = E_{jdt, Load}(t) < [P_{j=MHG}(t) \times \eta_{MHG}] \times X_{j=MHG} \quad (13.10)$$

i.e.

$$\begin{aligned} E_{jdt}(t) &= E_{jdt, Load}(t) + E_{jdt, BATT}(t) + E_{jdt, Dump}(t) \\ &= P_{j=MHG}(t) \times \eta_{MHG} \end{aligned}$$

$$E_{jdt}(t) = E_{jdt, Load}(t) \geq [P_{j=MHG}(t) \times \eta_{MHG}] \times X_{j=MHG} \quad (13.11)$$

i.e.

$$E_{jdt}(t) = E_{jdt, Load}(t) = P_{j=MHG}(t) \times \eta_{MHG}$$

6.7. Decision variables and constraints associated with BGG

The generation characteristics and constraints associated with BGG are given below.

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) < [P_{j=\text{BGG}}(t) \times \eta_{\text{DFEG}}] \times X_{j=\text{BGG}} \quad (13.12)$$

i.e.

$$\begin{aligned} E_{jdt}(t) &= E_{jdt, \text{Load}}(t) + E_{jdt, \text{BATT}}(t) + E_{jdt, \text{Dump}}(t) \\ &= P_{j=\text{BGG}}(t) \times \eta_{\text{DFEG}} \end{aligned}$$

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) \geq [P_{j=\text{BGG}}(t) \times \eta_{\text{DFEG}}] \times X_{j=\text{BGG}} \quad (13.13)$$

i.e.

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) = P_{j=\text{BGG}}(t) \times \eta_{\text{DFEG}}$$

6.8. Decision variables and constraints associated with BMG

The generation characteristics and constraints associated with BMG are expressed as:

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) < [P_{j=\text{BMG}}(t) \times \eta_{\text{DFEG}}] \times X_{j=\text{BMG}} \quad (13.14)$$

i.e.

$$\begin{aligned} E_{jdt}(t) &= E_{jdt, \text{Load}}(t) + E_{jdt, \text{BATT}}(t) + E_{jdt, \text{Dump}}(t) \\ &= P_{j=\text{BMG}}(t) \times \eta_{\text{DFEG}} \end{aligned}$$

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) \geq [P_{j=\text{BMG}}(t) \times \eta_{\text{DFEG}}] \times X_{j=\text{BMG}} \quad (13.15)$$

i.e.

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) = P_{j=\text{BMG}}(t) \times \eta_{\text{DFEG}}$$

6.9. Decision variables and constraints associated with DEG

The following equations represent the generation characteristics and constraints associated with DEG. They imply that the power generation from the DEG at any hour t can take the value zero, or any value between its minimum generation (which is assumed to be 80% of its rated power), and its maximum generation capacity (which is its rated power), if the DEG is selected.

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) < [P_{j=\text{DEG}}(t) \times \eta_{\text{DEG}}] \times X_{j=\text{DEG}} \quad (13.16)$$

i.e.

$$\begin{aligned} E_{jdt}(t) &= E_{jdt, \text{Load}}(t) + E_{jdt, \text{BATT}}(t) + E_{jdt, \text{Dump}}(t) \\ &= [0.8P_{j=\text{DEG}}(t), 1.0P_{j=\text{DEG}}(t)] \times \eta_{\text{DEG}} \end{aligned}$$

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) \geq [P_{j=\text{DEG}}(t) \times \eta_{\text{DEG}}] \times X_{j=\text{DEG}} \quad (13.17)$$

i.e.

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) = [1.0P_{j=\text{DEG}}(t)] \times \eta_{\text{DEG}}$$

Finally, diesel generator should have time limits of operation to reduce wear and tear.

$$\sum_{t=1}^{24} X_{j=\text{DEG}} \leq T_{\text{DEG}} \quad (13.18)$$

$$0 \leq T_{\text{DEG}} \leq K \quad (13.19)$$

where K is the maximum permissible time to operate the generator daily and T_{DEG} number of running hours daily.

6.10. Decision variables and constraints associated with BATT

Similarly, the generation characteristics of BATT implies that the discharging from the battery at any hour t can take the value zero, or any value between its minimum discharge capacity (which is assumed to be 20% of its rated capacity), and its maximum discharge capacity (which is its battery rated capacity), if the battery is selected, where, $P_{j=\text{BATT}}$ is the rated capacity of battery bank.

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) < [P_{j=\text{BATT}}(t) \times \eta_{\text{DCHG}}] \times X_{j=\text{BATT}} \quad (13.20)$$

i.e.

$$\begin{aligned} E_{jdt}(t) &= E_{jdt, \text{Load}}(t) / (\eta_{\text{INV}} \times \eta_{\text{DCHG}}) \\ &= [0.2P_{j=\text{BATT}}(t), 1.0P_{j=\text{BATT}}(t)] \times \eta_{\text{DCHG}} \end{aligned}$$

$$E_{jdt}(t) = E_{jdt, \text{Load}}(t) \geq [P_{j=\text{BATT}}(t) \times \eta_{\text{DCHG}}] \times X_{j=\text{BATT}} \quad (13.21)$$

i.e.

$$E_{jdt}(t) = 0$$

Lastly, in order for the system with battery to be sustained over a long period of time, the battery SOC at the end of the day must be greater than a percentage of its SOC_{max} . This study assumes 80% as shown below:

$$\text{SOC}(t = 24) \geq 0.8\text{SOC}_{\text{max}} \quad (13.22)$$

7. Working of hybrid energy system optimization model

The hybrid energy system optimization model is broken down into two parts: A simulation-performance component and an economic-assessment component. The simulation is based on a steady state model which, by incorporating different renewable generators, diesel generator, battery storage, allows for a static model (based on hourly energy balance) to be used instead of an instantaneous operational dynamic model. The simulation-performance model, embodied in a C++ program, takes description of the village load, generating components, and performs an hour-by-hour energy balance simulation where energy flows from component to component and the village load are calculated.

7.1. The simulation-performance model

An algorithm attempts to meet hourly village loads while attempting to maximize micro-hydro and other renewable energy utilization and minimize use of the diesel generator.

The model calculates the maximum amount of renewable energy available for a given hour based on the number of renewable generators available in that hour. Then by comparing the available energy with the village's electric needs it will meet that need, charge the batteries, and in the event of excess capacity divert energy to a dump load. If the renewable energy is insufficient, the model then chooses the combination of the battery bank storage and diesel generator which best meets the netload given component availability in that hour. In choosing between battery and diesel power, the model selects battery storage whenever the available battery energy can meet the entire netload. In the event there is not sufficient battery power, the diesel generator is turned on with excess energy diverted to battery charging and dump load. In the event that all the renewable generators, diesel generator and battery storage units are insufficient to

meet village load, then in that case, there will be a portion of demand unmet (i.e. unmet energy).

7.2. The economic-assessment model

The performance model yields the generation characteristics of the model such as total generation by renewable generators, diesel generator and battery bank, and how much energy went direct to village load, to charge batteries and so forth. This information is then combined with the unit cost of system components to determine the optimum total cost of electricity. The sum of optimum cost is then divided by the quantity of electrical energy actually delivered to the village, to calculate the optimum unit cost of electricity (Rs/kWh) of the hybrid energy system.

8. Conclusions

Taking into consideration the scientific interest concerning the capabilities of hybrid energy systems with energy storage to fulfill the electrification needs of a rural remote area, a detailed mathematical model of describing the operational behavior of the basic hybrid energy system components is presented.

The proposed model employs integer linear programming to determine the optimum unit cost and operation of the hybrid energy system with a storage facility, using hourly, daily and monthly load demand. The model is shown to be sufficiently accurate. It uses the original load curves instead of the load duration curves, accurately reflecting the time dependency of the storage operation policies over a year.

The proposed model can be used in planning studies to determine the optimum design of an autonomous hybrid energy system.

References

- [1] Young SK. Integrated solar energy system optimization. *Journal of Solar Energy Engineering* 1982;104(4):310–6.
- [2] Contaxis GC, Kabouris J, Chadjivassiliadis J. Optimum operation of an autonomous energy system. In: *Proceedings of EWEC '86*; 1986. p. 305–10.
- [3] Swaminathan S, Kottathra K, Phillips S, Teh K. A MNL formulation for power system scheduling. In: *Proceedings of SOLAR '93*; 1993. p. 446–51.
- [4] Chen M, Atta-Konadu R. Mathematical programming model for energy system design. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 1997;19(8):789–801.
- [5] Kandil MS, Farghal SA, El-Alfy AE. Optimum operation of an autonomous energy system suitable for new communities in developing countries. *Electric Power Systems Research* 1991;21:137–46.
- [6] Contaxis GC, Kabouris J. Short term scheduling in a wind/diesel autonomous energy system. *IEEE Transactions on Power Systems* 1991;6(3):1161–7.
- [7] Bakirtzis AZ, Gavanidou ES. Optimum operation of a small autonomous system with unconventional energy sources. *Electric Power Systems Research* 1992;23:93–102.
- [8] Connors SR, McGowan JG, Manwell JF. Wind/diesel village-scale electric power systems: the performance and economic analysis of a simulated village system. *Solar & Wind Technology* 1990;7(4):423–39.
- [9] Gavanidou ES, Bakirtzis AZ, Dokopoulos PS. A probabilistic method for the evaluation of the performance of wind-diesel energy systems. *IEEE Transactions on Energy Conversion* 1992;7(3):418–25.
- [10] Prasad AR, Natarajan E. Optimization of integrated photovoltaic-wind power generation systems with battery storage. *Energy* 2006;31:1943–54.
- [11] Wies RW, Johnson RA, Agarwal AN, Chubb TJ. Simulink model for economic analysis and environmental impacts of a PV with diesel–battery system for remote villages. *IEEE Transactions on Power Systems* 2005;20(2):692–700.
- [12] Jana C, Chattopadhyay RN. Block level energy planning for domestic lighting – a multi-objective fuzzy linear programming approach. *Energy* 2004;29:1819–29.
- [13] Ashok S. Optimised model for community based hybrid energy system. *Renewable Energy* 2007;32:1155–64.
- [14] Gupta A, Saini RP, Sharma MP. Modelling of hybrid energy system for off-grid electrification of clusters of villages. *Proceedings of IEEE, India*; 2006:1–6.
- [15] Gupta A, Saini RP, Sharma MP. Design of an optimal hybrid energy system model for remote rural area power generation. *Proceedings of IEEE, Pakistan*; 2007:1–6.
- [16] Jebaraj S, Iniyan S. A review of energy models. *Renewable & Sustainable Energy Reviews* 2006;10:281–311.
- [17] Hiremath RB, Sikha S, Ravindranath NH. Decentralized energy planning: modeling and application. *Renewable & Sustainable Energy Reviews* 2007;11:729–52.
- [18] Nouni MR, Mullick SC, Kandpal TC. Biomass gasifier projects for decentralized power supply in India: a financial evaluation. *Energy Policy* 2007;35:1373–85.
- [19] Singh KJ, Sooch SS. Comparative study of economics of different models of family size biogas plants for state of Punjab, India. *Energy Conversion & Management* 2004;45:1329–41.
- [20] Diaf S, Diaf D, Balhamel M, Haddadi M, Louche A. A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy* 2007;35:5708–18.
- [21] Lagunas J, Caratozzolo P, Ortega C, Gonzalez R. Model design of wind/pv/fossil-fuel hybrid systems. *Proceedings of IEEE*; 2004:403–8.
- [22] Arivalagan A, Raghavendra BG, Rao ARK. Integrated energy optimization model for a cogeneration based energy supply system in the process industry. *Electrical Power and Energy Systems* 1995;17(4):227–33.
- [23] Pipattanasomporn M. A study of remote area internet access with embedded power generation. PhD thesis, Virginia Polytechnic and State University, Virginia; 2004.